CONSTRUCTION OF FIELD WINDINGS FOR A SUPERCONDUCTING ALTERNATOR

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ABSTRACT

Construction techniques are described for a helium cooled superconducting field winding of an experimental 3600 rpm alternator having an anticipated rating of 2 MVA. Winding procedures are presented for a 2 pole field magnet composed of six concentric layers of superconducting wire banded with glass roving and epoxy. Jigs built to aid in the fabrication process are described.

A stress analysis on a simple model of the winding structure leads to a required prestress level in the glass bands to prevent layer separation when the machine is operating. A filament banding program is recommended which gives a uniform stress level in the glass banding.

Thesis Supervisor: Philip Thullen
Title: Assistant Professor of Mechanical Engineering

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GLOSSARY OF SYMBOLS

Symbol	Meaning
B	magnetic flux density
E_g, E_s	modulus of elasticity of glass, stainless steel
F, F_ρ	force, radial force
J, J_f	current density, field current density
L	length of wire bend
ℓ	axial length
P_c	contact pressure
P_{csc}, P_{cgl}	contact pressure due to rotational forces on superconducting wire, glass
P_m	pressure from magnetic forces
P_1'	internal pressure
R	radius from rotor axis
R_1	inner field radius
R_2	outer field radius
R_{si}	inner radius of stainless stell hoop
$\overline{R_s}$	average radius of stainless steel hoop
R_{ci}	inner radius of superconducting wire hoop
$\overline{R_c}$	average radius of superconducting wire hoop
R_{gi}	inner radius of glass hoop
$\overline{R_g}$	average radius of glass hoop
R_w	large radius of curvature of superconducting wire for end turn bend
r	radius
r_1	inner radius of hollow cylinder
r_2	outer radius of hollow cylinder

GLOSSARY OF SYMBOLS (continued)

Symbol	Meaning
r_3	outer radius of winding around hollow cylinder
t_s	thickness of stainless stell hoop
t_c	thickness of superconducting wire hoop
t_g	thickness of glass hoop

GREEK LETTERS

δ_p	pole face half angle
ε_{ts}	thermal strain in stainless steel
ε_{tg}	thermal strain in glass
η	ρ/R_1
μ_0	magnetic permeability of a vacuum
ρ	radial cylindrical coordinate
ρ, ρ_c, ρ_g, ρ_s	density, density of superconducting wire, glass, stainless steel
σ_g	glass hoop stress
σ_w	winding tension stress
σ''_t	uniform winding prestress
σ_t	final varying winding prestress
ϕ	angular cylindrical coordinate
ω	radian frequency of rotor

CHAPTER I

Introduction

The development of superconductors capable of operation with high current densities in high magnetic fields has led to the use of superconductors in large stationary magnets. In addition, studies have been undertaken (1) which show that major improvements can be realized when superconductors are used in rotating electric machines. Chief among these are significant reductions in size and weight for a given power output with improved efficiency.

The implications to the power generation industry are readily apparent. In order to take advantage of improved performance and to achieve greater efficiency turbo-generators have grown in size until today when several factors inhibit further growth. Among these are strength limitations, cooling problems, vibrational considerations, forging limitations, transient reactance problems, and shipping difficulties. A severe strain is being placed on present technology at a time when power requirements are increasing rapidly.

Any successful use of superconductors in electric machinery will have significant impact on naval and commercial ship propulsion systems. A major problem in ship propulsion lies in transmitting power from a prime mover which operates efficiently at high rpm to a propulsive device which operates most efficiently at relatively low rpm. Reduction gears are often used to make the necessary transition, but they are

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bulky, noisy, and heavy, normally accounting for up to 10% of the entire propulsion plant weight. Turbine electric drives offer a means of eliminating the reduction gearing by accomplishing the necessary speed reduction electrically. However, conventional electric drives are normally 20% heavier than equivalent geared plants, as well as being more expensive and less efficient.

A recent M.I.T. thesis by David L. Greene (2) showed that the use of superconducting machines can eliminate the weight penalty inherent with conventional electric machinery. When a propulsive system employing a gas turbine prime mover, a synchronous generator and synchronous motor with superconducting field windings, and a cycloconverter, was substituted for the existing CODOG system on the USCGC HAMILTON WHEC-715, a weight comparison showed a reduction of 27% in machinery weight.

Benefits may be realized in using superconductors in both AC and DC electric machines. Both uses are being actively pursued, and are in the building, experimental, and developmental stages. Prototypes of homopolar machines have been built and one is in service as a condenser cooling water pump in a power station at Fawley, England (3). Their use has also been proposed for naval propulsion plants, and active programs are being pursued both in England and the United States.(4) Experimental AC machines have also been built and tested.(1,5) Of the various possible uses of superconductors in AC machines, the most feasible appears to

be using the superconductors for a rotating field winding. Problems of constructing the rotating low temperature dewar and of providing continuous transfer of liquid helium to the rotating winding have proven solvable as demonstrated by the M.I.T. 80 KVA synchronous alternator. (5,6)

The next step in the development process at M.I.T. is to apply the knowledge and experience gained from the 80 KVA machine on a second experimental machine whose nominal output will be 2 MVA. This thesis describes the construction techniques and tools necessary for fabricating the field winding of this machine.

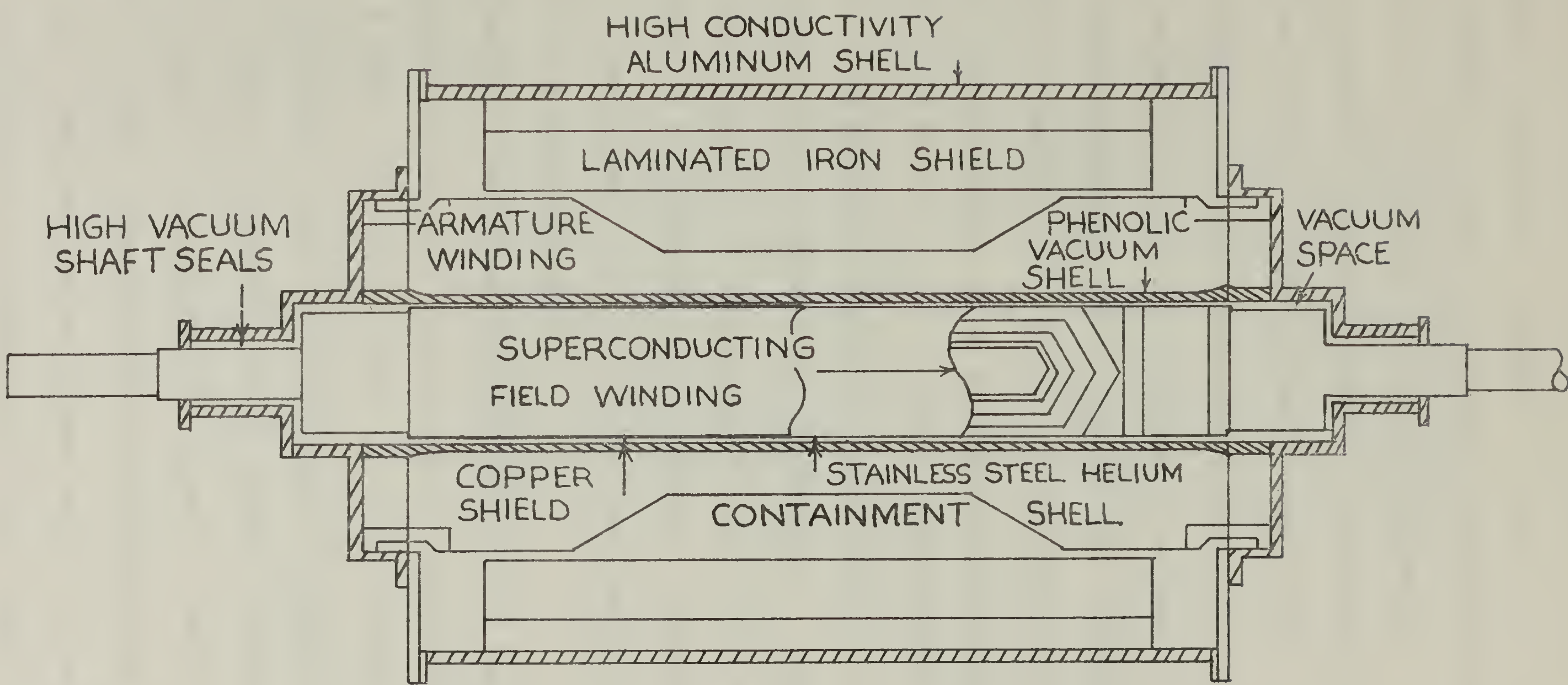
CHAPTER II

Field Winding Description

The rotating superconducting field winding described in this thesis is part of an experimental 3600 rpm alternator of 2 MVA anticipated rating being built at M.I.T. Figure 2.1 shows this machine. Elimination of ferromagnetic material from the rotor, and the need for adequate liquid helium cooling passages in the superconducting field winding cause a significant departure from conventional field winding geometry. It is therefore desirable to describe the rotor structure and field winding in some detail.

The rotor, of which the field winding is a part, is a low temperature structure which provides the necessary environment to maintain the superconducting properties of the wire. It is the only low temperature section of the machine. The rotor tube is a six inch diameter stainless steel cylinder approximately $\frac{1}{2}$-inch thick. Superconducting winding fills two 120° annuli approximately one inch thick and forty inches in length around this tube. Current leads for the superconducting wire as well as tubing for helium inlet and outlet passages pass through the vacuum space on the inside of the rotor. Details of rotating seals to maintain this vacuum are described in the M.I.T. S.M. thesis of John Murphy. (7)

The two pole field winding is wound in place on the rotor making twelve interconnected saddle coils, of



MIT 2MVA SUPERCONDUCTING ALTERNATOR

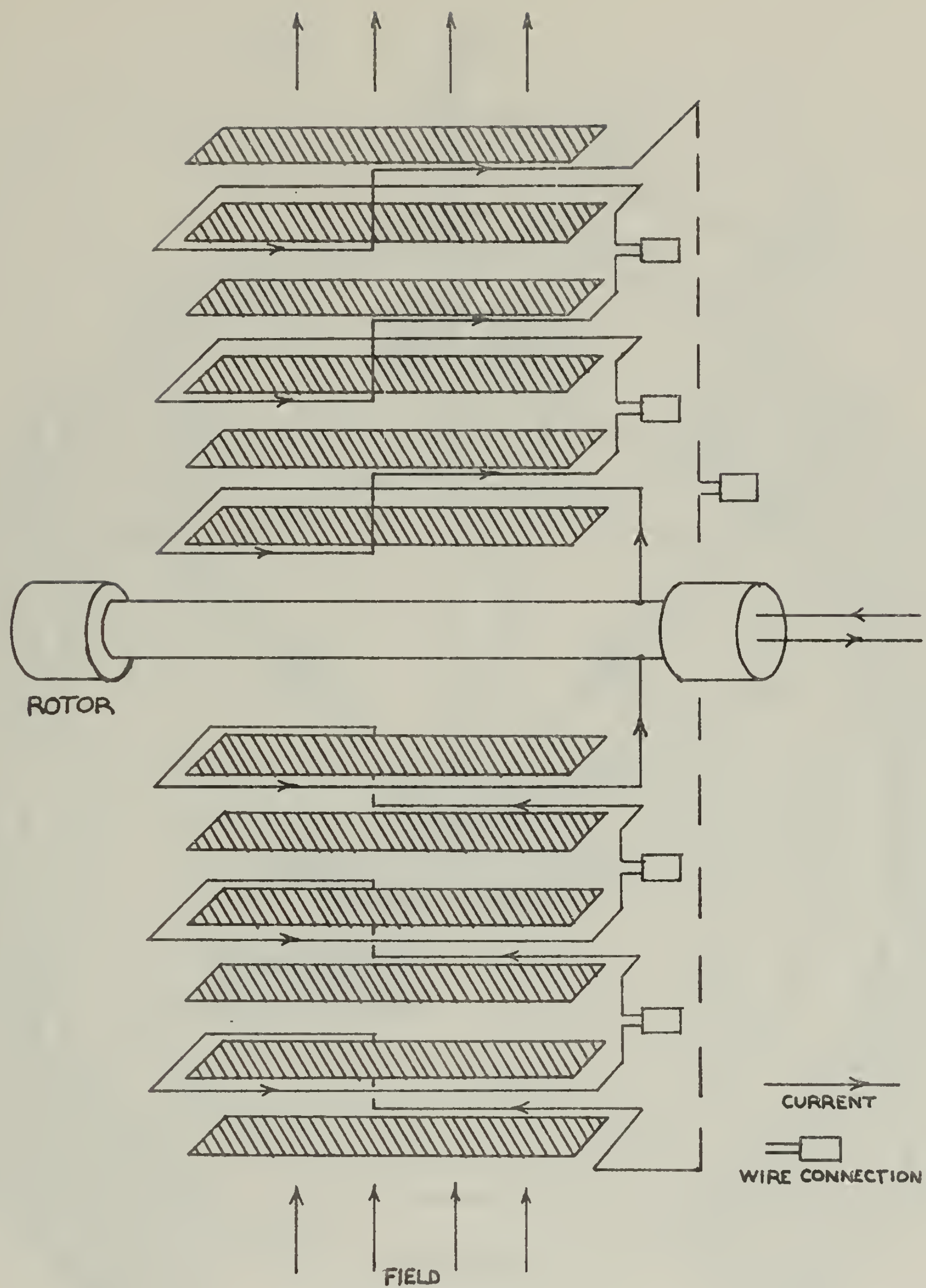
FIGURE 2.1

approximately 750 turns, forming a magnet with 60° open pole faces. This is shown in figures 2.2 and 2.3. Winding geometry can best be seen by figure 2.4, which shows a plane projection of the cylindrical winding geometry. Superconducting wire makes three 60° bends at each end turn. This allows the end turns to be properly supported. Micarta, of the same thickness as the superconducting wire, is used for the pole pieces and end turn pieces to support the winding.

The superconducting wire used in the construction of the field winding consists of strands of niobium-titanium superconducting wire embedded in a rectangular matrix of copper, The outside surface is electrically insulated by a copper oxide layer. Figure 2.5 shows a cross section of the wire, which is described in detail in Appendix A. Since the wire remains perpendicular to the cylindrical rotor at all times, a helical path is followed by the wire at the end turns. Chapter III describes the tools that are used for bending the wire to fit this geometry.

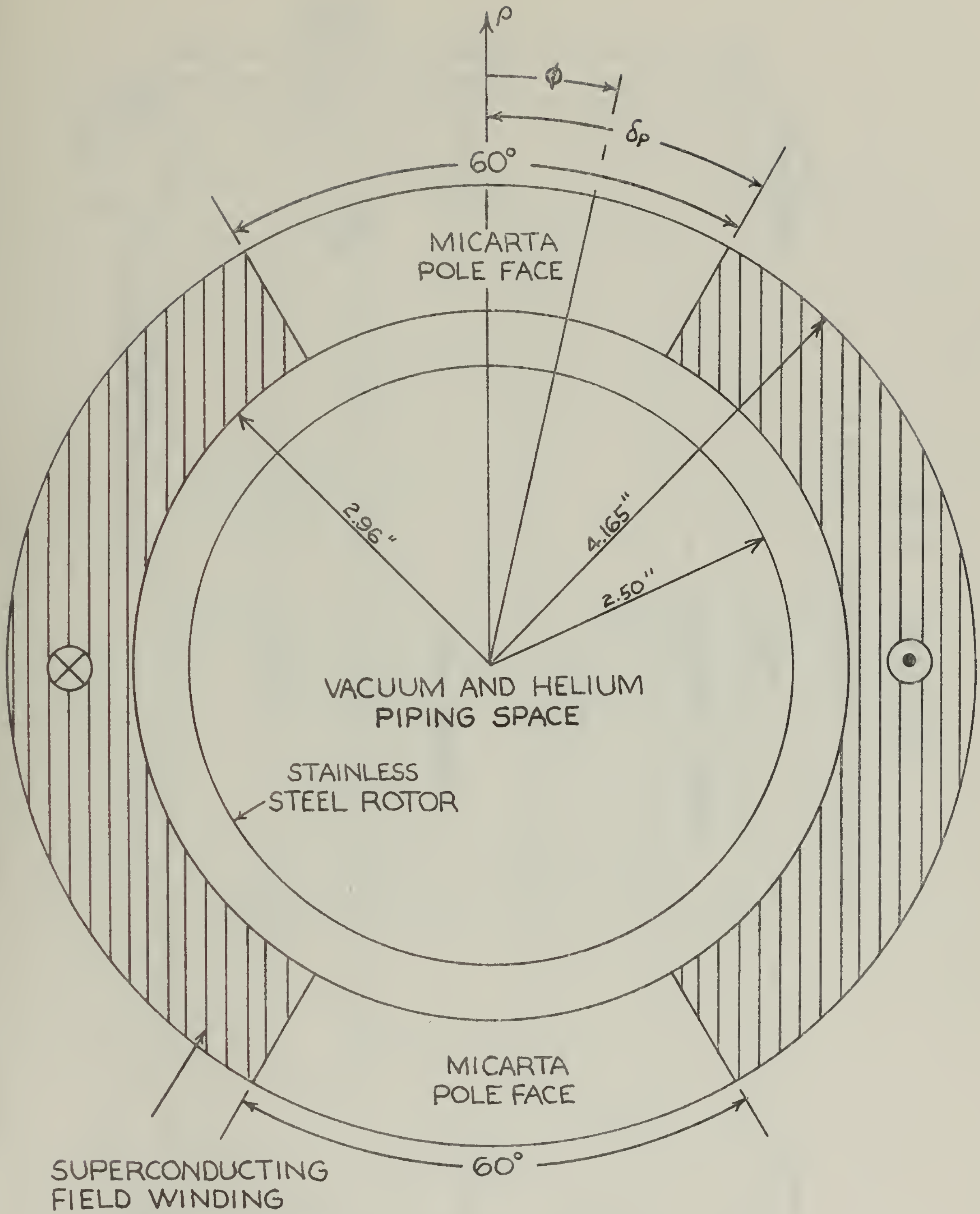
Superconducting wires forming the coils are sandwiched between layers of type "S" glass-epoxy bands $\frac{1}{4}$-inch wide spaced at $\frac{1}{4}$-inch intervals along the axis of the rotor. The material for these bands is described in Appendix A, and the winding layer structure can be seen in figure 2.6.

Banding provides mechanical support against rotational and magnetic forces, electrically insulates the superconducting wires, and maintains spaces which allow adequate cooling of each wire to prevent the wire from going normal.

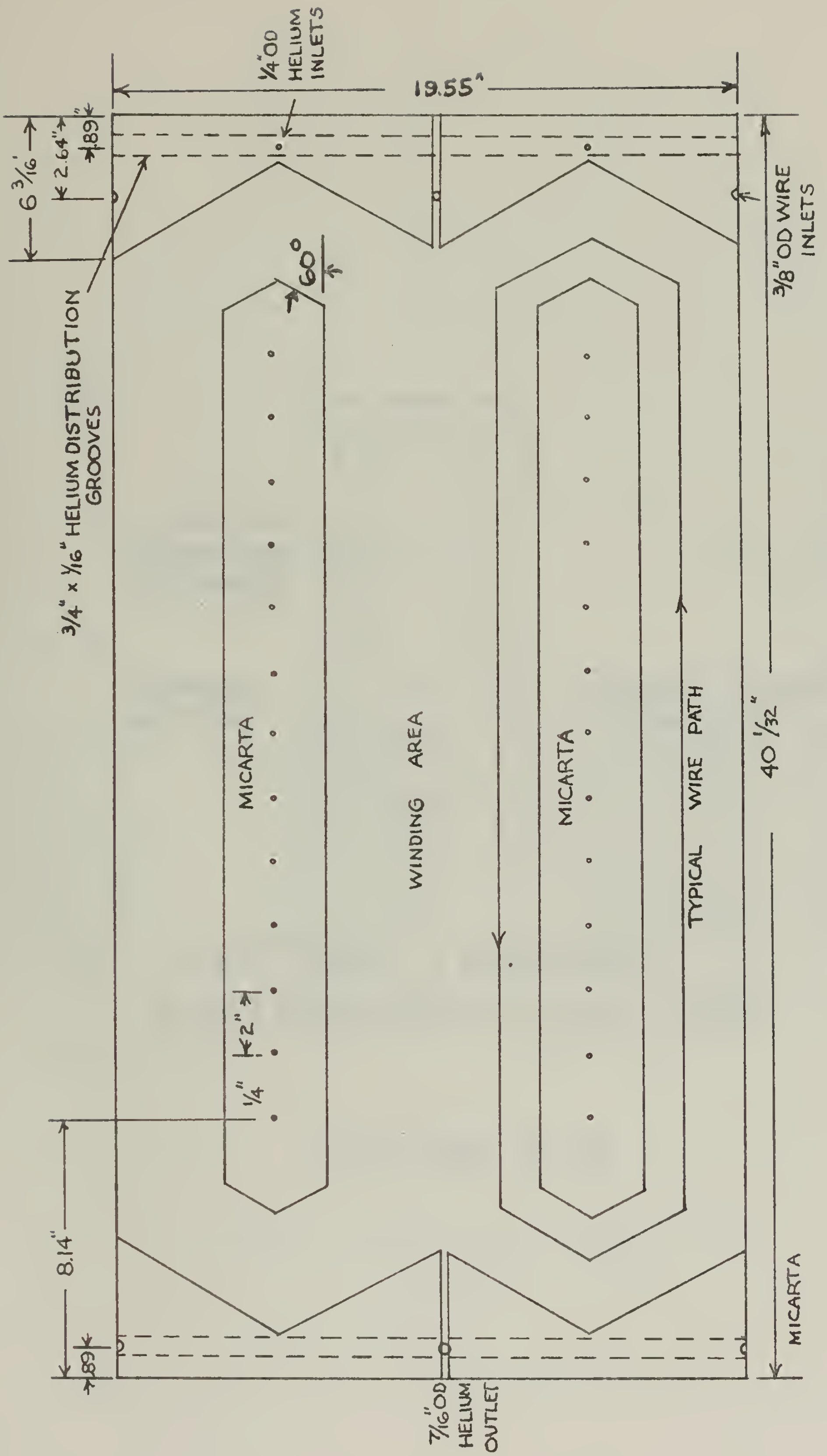


FIELD WINDING SCHEMATIC

FIGURE 2.2

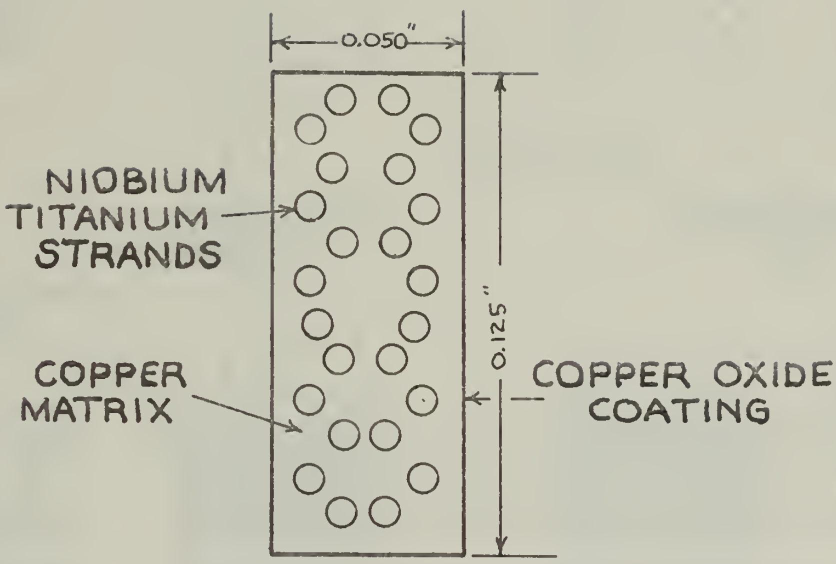


ROTOR CROSS SECTION
FIGURE 2.3



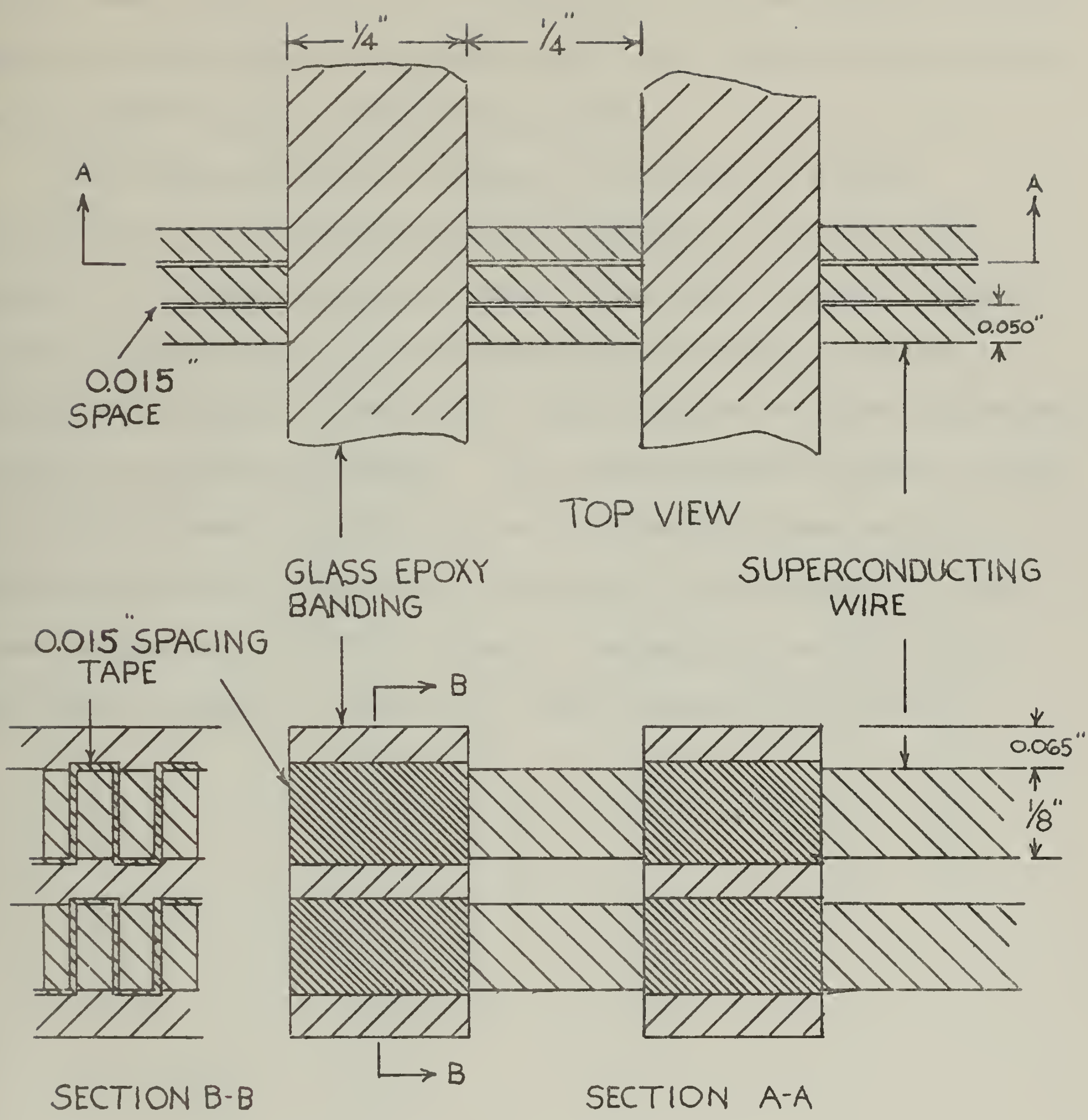
INSIDE WINDING LAYER

FIGURE 2.4



SECTION THROUGH SUPERCONDUCTING WIRE

FIGURE 2.5

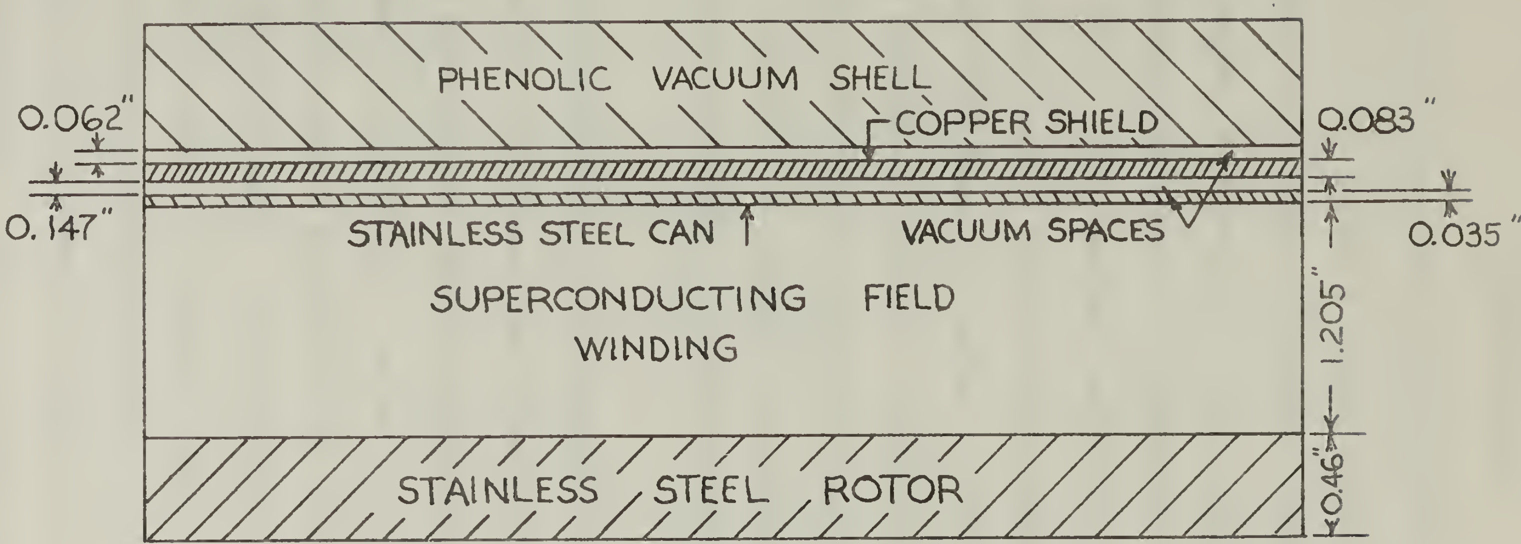


FIELD WINDING SUPPORT STRUCTURE

FIGURE 2.6

Within each layer, wires are separated and insulated by ¼-inch bands of semi-cured insulating tape 0.015 inches thick spaced to coincide with the glass-epoxy bands.

The completed field winding is encased in a thin cylindrical stainless steel shell welded to the rotor end pieces. A vacuum space separates this from a copper electro-thermal shield which is attached to the thermal distance pieces at the end of the rotor and is cooled by heat exchangers formed by the helium tubing. The electrothermal shield along with the thermal distance pieces and vacuum space minimize heat transfer by radiation, convection, and conduction from room temperature to the cryogenic temperature maintained in the field winding. Figure 2.7 shows these rotor details.



ROTOR SECTION

FIGURE 2.7

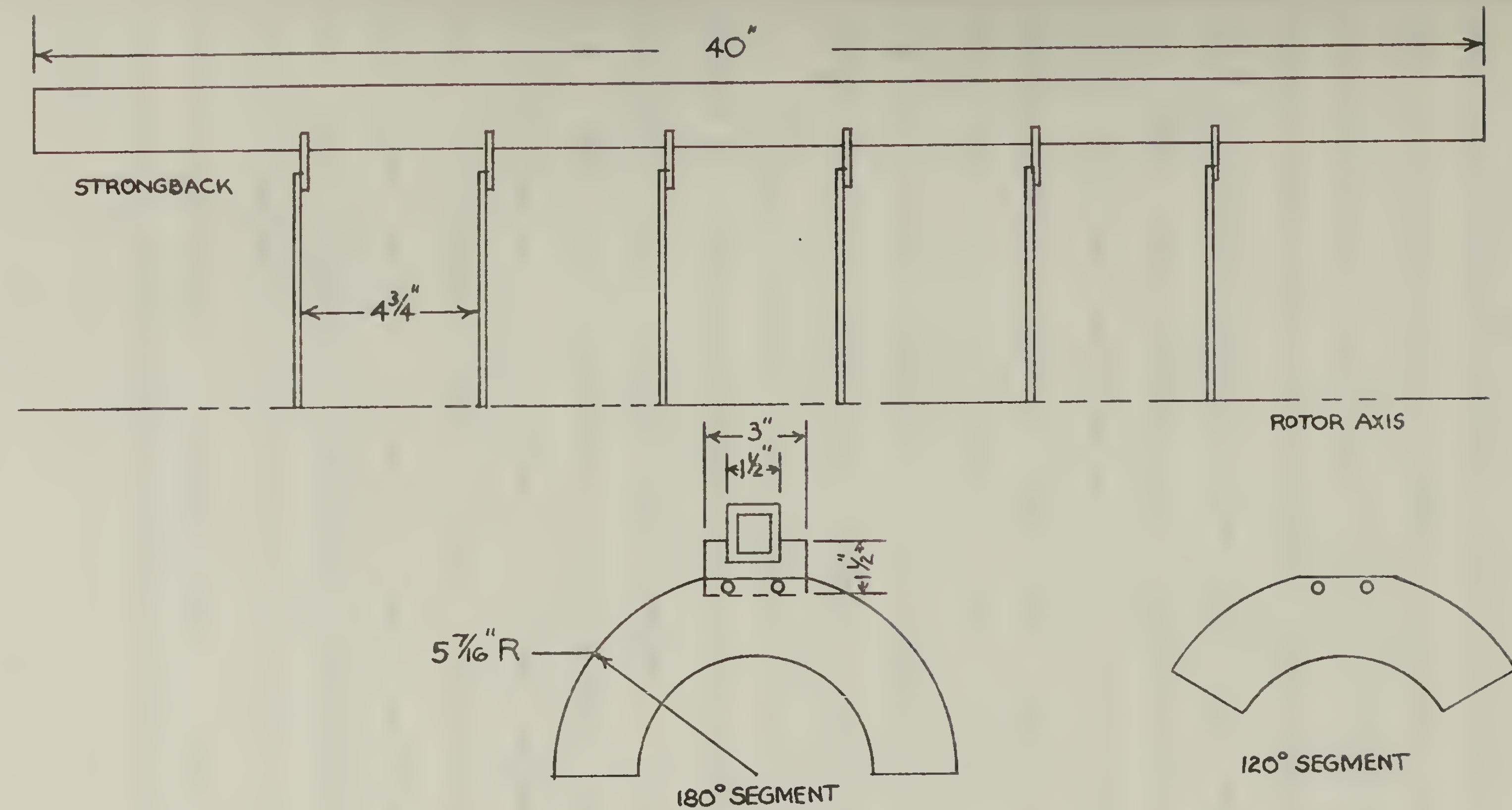
CHAPTER III

Winding Jigs

Three winding jigs were constructed as part of this thesis to aid in the winding process. The first consists of two strongbacks with sets of removable hold down segments to be used to temporarily position the superconducting wire on the rotor before each layer is permanently banded in place with glass roving. The second and third are wire benders for bending the wire to fit the end turn geometry. One, patterned after a common tube bender, bends the wire in the large radius of curvature needed to follow a helical path around the rotor. The other makes 60° bends needed at each end turn. In this chapter each jig will be described together with its use and major considerations made in choosing jig configurations and dimensions.

The two strongbacks are of welded angle iron construction and are supported one above each micarta pole piece by studs which extend through the pole piece from the rotor. Along each strongback are welded a set of six equally spaced brackets. Each bracket supports one circular segment perpendicular to the rotor axis. The inside diameter of each segment forms an annulus with the rotor winding structure into which the superconducting wire is placed as it is wound. The strongback jig is shown in figure 3.1.

The configuration chosen for the strongback jig compromises the need for adequate wire support with the desire for ease in winding and a minimum amoung of jigging. Although

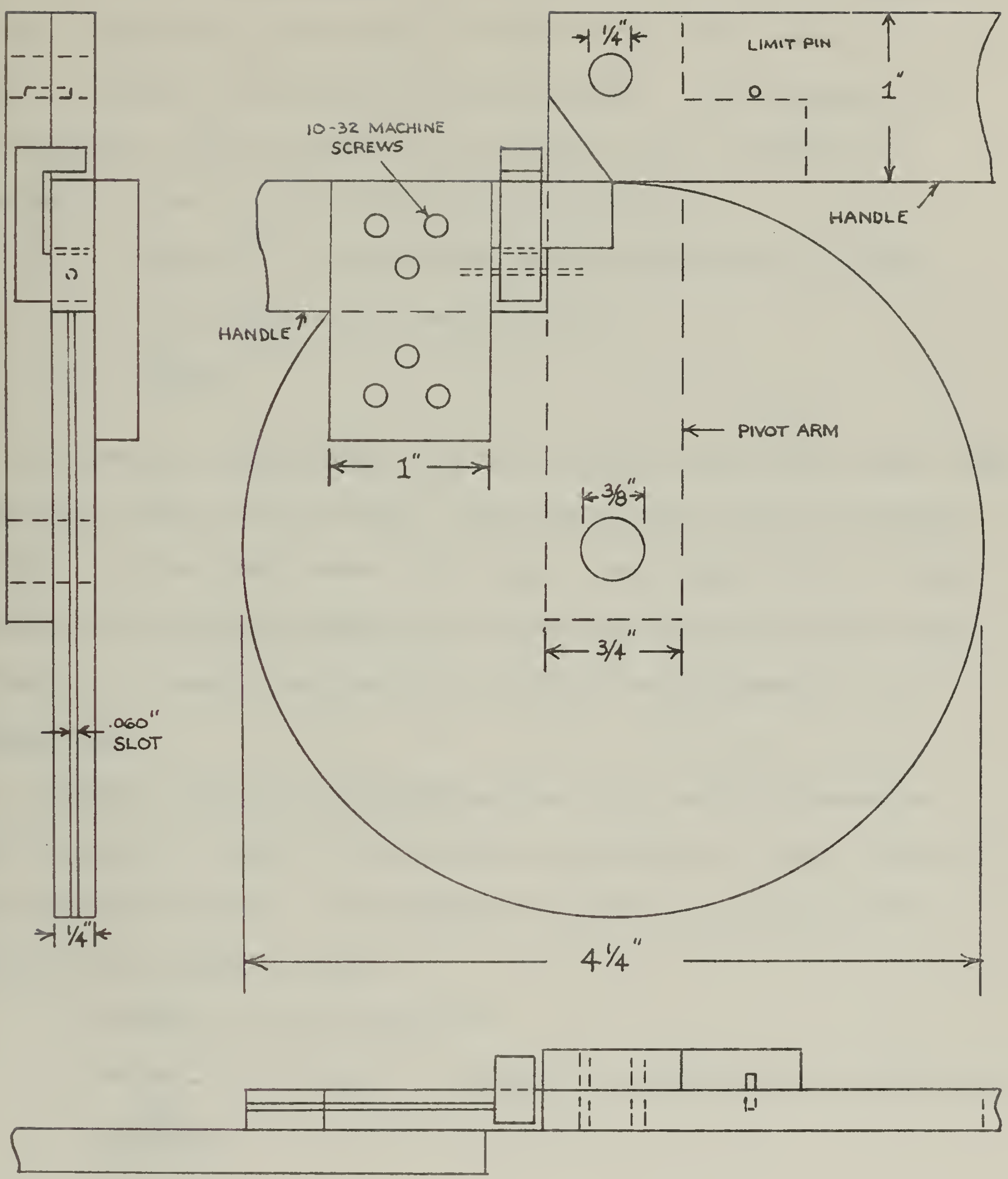


STRONGBACK WIRE HOLD DOWN APPARATUS

FIGURE 3.1

brackets are provided for six support segments on each strongback, fewer can be used if the winding operation permits. To speed the winding process, two sets of removable segments were made. One set covers a 120° arc of the rotor and is used at the beginning of winding. As the winding progresses and the annulus under the 120° segments fills with wire, the segments can be replaced one at a time with 180° segments to complete the layer. The segments are designed with a large enough radius so that they can be used on the outside as well as the inside winding layers. After each layer is completed, steel hoops hold the wire layer in place for the banding operation, and the inside diameter of the segments is turned to the larger diameter needed for holding the next layer of winding.

A jig for bending the superconducting wire in the large radius of curvature needed for the end turn geometry was patterned after a common tube bender. It is shown in figure 3.2. The jig is portable and used much like a tube bender. Straight wire is fed along a grooved segment tangent to a slot in a circular disc. While a hold down arm clamps and positions the wire along the feeder section preventing the wire from slipping, a follower arm pivoting on the center of the disc makes the wire follow the slot around the disc bending the wire to desired length. This bend is the one necessary for the wire to follow a helical path at the end turns.



LARGE RADIUS WIRE BENDER

FIGURE 3.2

One factor considered in choosing the circular dimension of the bender was the amount of bend which must be put in the wire to follow the required helical path. For purposes of the bending tool this path is circular with a radius of curvature given by the following expression.

R_w = radius of curvature of superconducting wire path

R = radius from rotor axis to wire

$$R_w = \frac{R}{\cos 30°}$$

To perform adequately the wire bender must first make the smallest radius of curvature required at the inside winding layer. It also must make the larger bends required at outer layers. The outer layers are no problem since once the wire is bent to a small radius it is easily hand formed to a larger one.

Another factor in selecting the wire bender dimension was the need to make it as large as possible to make bends of the required length. An expression gives the relation for finding the needed length.

L = length of required bend

ϕ = angular distance in radians in cylindrical coordinates

$$L = \frac{\phi R}{\cos 30°}$$

Unfortunately, for the bender needed for the given geometry, both constraints could not be satisfied simultaneously. The circular dimension chosen gives the required bend at the inner radius after springback. A bend of adequate length can

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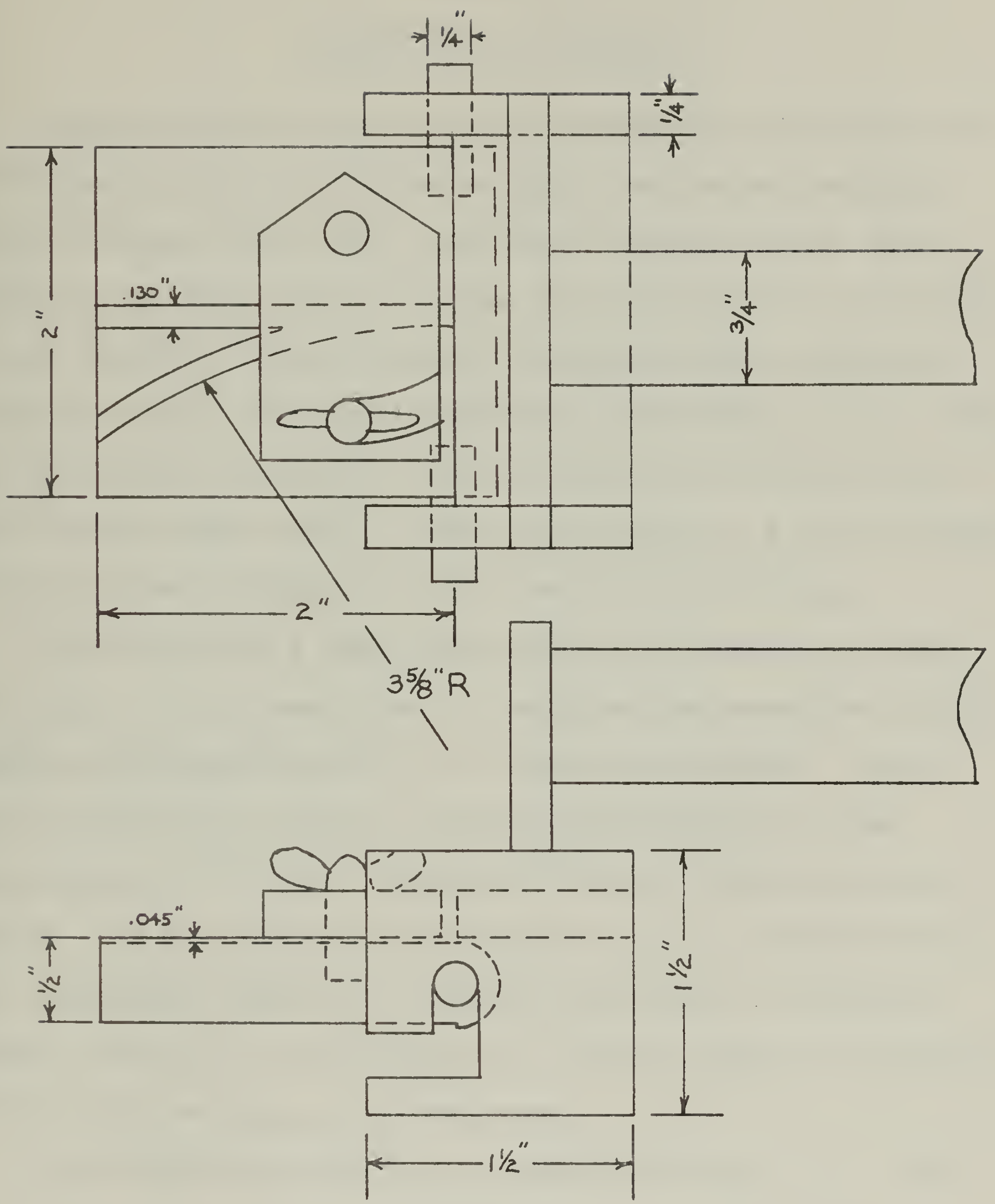
be made for the inner layers, but the outer layer bends require the wire to be repositioned in the tool to get the needed length.

A small radius of curvature bender is shown in figure 3.3. It is used to make the 60° bends for each end turn after the large radius of curvature has already been made by the bender previously described. The wire is held in place in a slot while a removable hand held follower pivots around a $\frac{1}{4}$-inch radius end piece until the 60° bend is made. The $\frac{1}{4}$-inch bend radius was chosen because it produced a reasonably sharp bend without damage to the superconducting strands.

This chapter described the individual winding jigs built to construct the winding accurately and conveniently. How the winding jigs and their uses fit into important winding procedures is discussed in Chapter IV.



60° ANGLE WIRE BENDER

FIGURE 3.3

CHAPTER IV

Construction Procedure

Superconducting wire is to be wound onto the rotor in a configuration which provides adequate mechanical support, insures proper electrical insulation between wires, and promotes the free flow of helium to uniformly cool all parts of the winding. Understanding the construction procedure leading to this structure requires a description of the winding and banding sequence, the interlayer wire connections, and wire end turn bends. These steps lead to a field winding which performs according to its design expectations.

The choice of a type and location for devices to make interlayer wire connections is important because they affect machine performance as well as winding procedure. Since these connections cannot be made superconducting, they contribute to the heat load which must be removed by the helium. If the number of connections can be minimized and the connections made in a location which can be properly cooled, the helium requirement is reduced and local quenching of the field winding is eliminated.

The connections chosen are shown in figure 4.1. They are mechanical pigtail connections made by mechanically squeezing a copper sleeve over two superconducting wires after the copper oxide coating is removed. All connections are located on the helium inlet end, and are provided individual cooling passages through the micarta end sections

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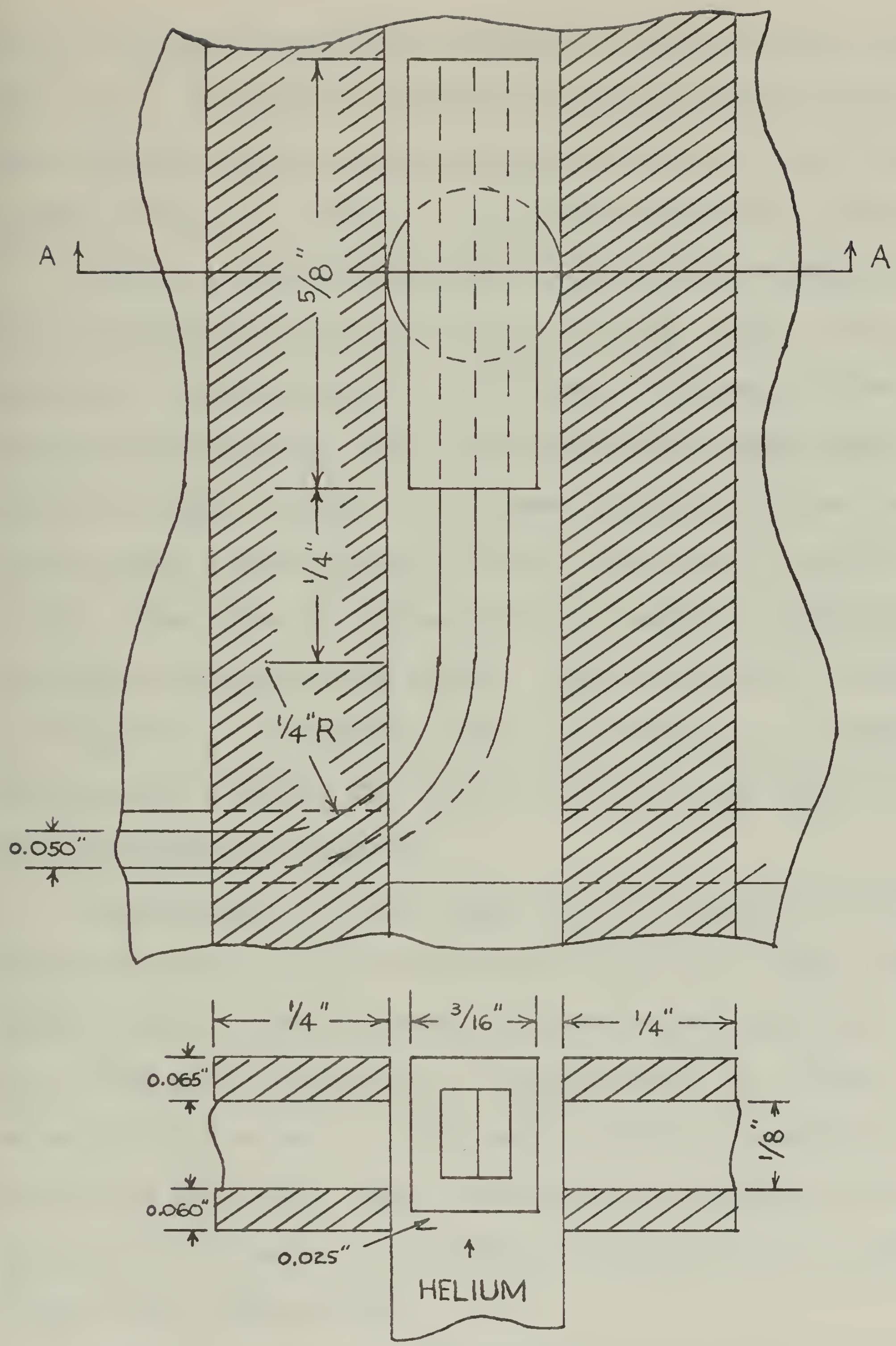


SECTION A-A

INTERLAYER WIRE CONNECTIONS

FIGURE 4.1

to the helium distribution groove to assure proper cooling. By using a continuous section of superconducting wire for two winding layers, only five connections of this type are needed. This is shown in the winding schematic of figure 2.2.

During the entire winding and banding sequence the rotor structure is positioned in a large lathe. The field winding is fabricated by alternately winding a layer of superconducting wire and then banding the completed layer with type "S" glass roving. A filament winding jig on the lathe feeds epoxy coated glass onto the rotor as it turns in the lathe. The epoxy is cured by heat lamps in a removable oven structure enclosing the rotor. Tension on the filament is controlled by a weighted lever arm acting on a capstan. Reasons for varying the tension on the glass as it is wound are discussed in Chapter V.

Construction of the field winding begins with the stainless steel rotor positioned in the lathe and ready to be banded with a spacing layer of glass-epoxy banding. A set of $\frac{1}{4}$-inch steel hoops are in place spaced at $\frac{1}{4}$-inch intervals along the rotor axis. They serve the dual purpose of pre-stressing the rotor tube and acting as forms for the banding operation. After the structure is wound and the epoxy is cured, they are removed.

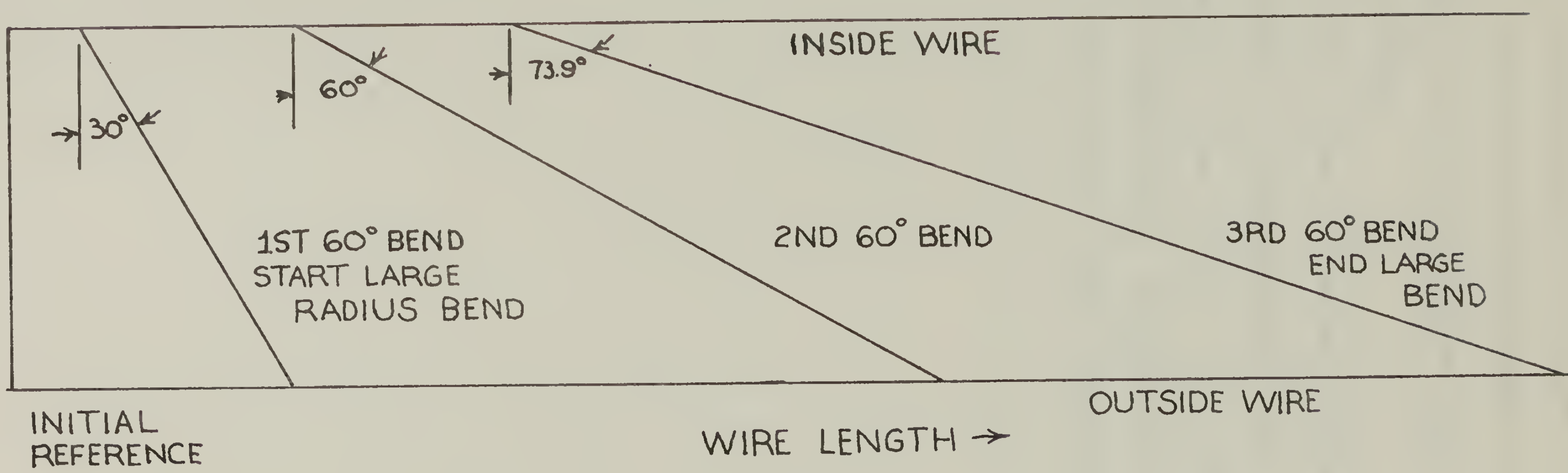
Micarta pieces for the pole face and end turn pieces are cut from micarta cylinders of the appropriate diameter. Pole face sections are positioned on the rotor over holes

along the pole centerline and held in place by the segments from the strongback hold down jig previously described.

After the bare rotor is banded and the pole face pieces and hold down jigs are in place, the first layer of superconducting wire can be wound. Wire for this operation is on two spools, one for the first layer, and one for the second. With the spool for the second layer located over the pole piece, wire from the other spool is used to wind the first layer, starting next to the pole piece and winding outward. The circular wire hold down segments hold the wire against the rotor after the wire turns are slipped into the annulus between the segments and the rotor.

The most difficult and time consuming part of the winding operation is bending the wire to fit the end turn geometry. Wire along the straight length of the poles is easily positioned and spacing between wires maintained with ¼-inch bands of spacing tape, but at the end turns care is taken to make sure that the bends are made at the proper location on all turns so that proper spacing is maintained. A constant reference mark established on a circular hold down segment is used to locate other marks for making the bends. The bending pattern within each layer varys linearly as the winding proceeds as shown in figure 4.2.

The reference marks from a calibrated bending pattern are used to position the wire in the bending tools so that the bends are located at the proper position. This assures



WIRE END TURN BENDING PATTERN

FIGURE 4.2

proper spacing is maintained in the end turns. Failure to do so results in a growth of the end turn area and a reduction both in the number of wire turns per layer and in the axial length of the winding.

When the first layer is wound, another set of steel hoops are installed to hold the wire while the strongback is removed and banding takes place. The remaining layers are completed in the same manner, alternately winding and banding the structure until the six layer structure is completed.

CHAPTER V

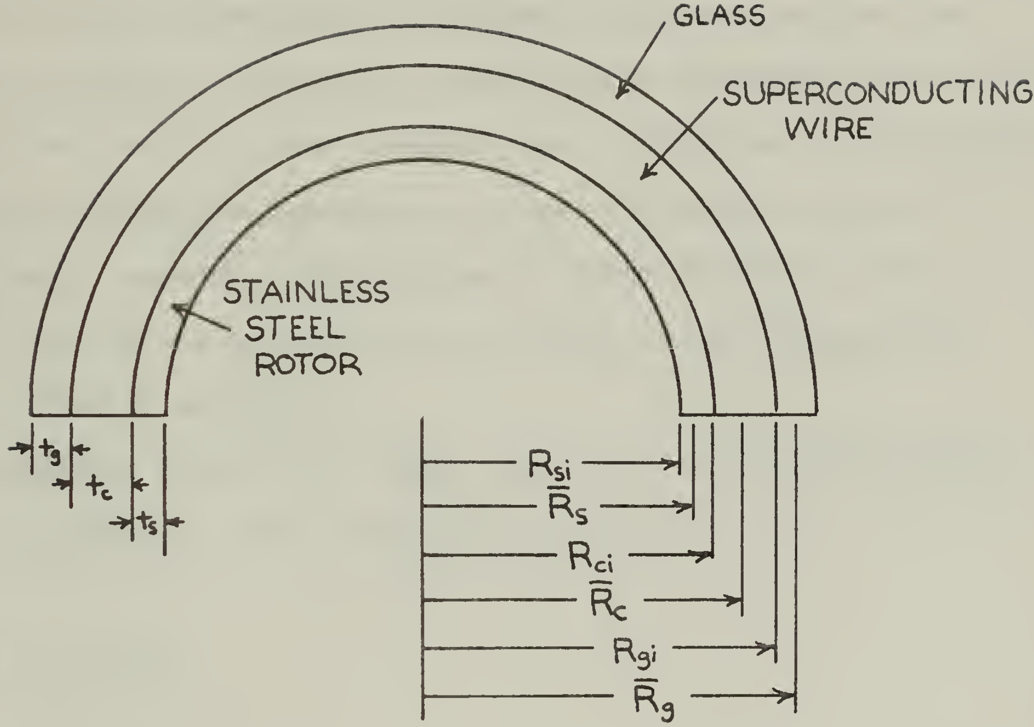
Banding Analysis

A stress analysis on the field winding structure is required in order that the following questions regarding the banding of the field winding with glass roving be answered.

1. Taking into consideration the difference in thermal contractions of the rotor and glass winding material, how much prestress is needed in the glass banding to prevent separation of the winding from the rotor at operating temperature due to magnetic and rotational forces?
2. Since the prestress levels in the glass banding layers are a function of the winding tension applied, what winding tension program is needed to insure that the stress in the bands are uniform when they are carrying their maximum load?

This chapter attempts to quantitatively answer these questions with reasonable accuracy using simple models and the dimensions and physical constants given in Appendix B.

Although the field winding structure is a complex one with the stainless steel rotor covered with alternate layers of wire and banding as shown in figure 2.6, a reasonable first order stress analysis of the structure may be performed with a three layer model shown in figure 5.1. This model allows hoop stress relations to be used. The tangential hoop stress in the glass-epoxy bands is assumed to be carried by the glass



THREE LAYER MODEL

FIGURE 5.1

fibers and is the result of rotational and magnetic pressure forces acting on the inside radius of the glass hoop.

Prestress, or set up stress, in the glass prevents the layers from separating by insuring a contact pressure exists between layers. The amount of prestress required to prevent layer separation depends on the magnitude of the rotational and magnetic forces and the amount of thermal contraction. Because of the difference in thermal contractions as the rotor is cooled to operating temperature prestress put in the glass when wound at room temperature is reduced. Fortunately, since the materials behave in a linear elastic manner, the rotational, magnetic, and thermal stress problems may be dealt with separately and the principle of superposition used to find a solution.

Magnetic forces are experienced by the current carrying wires according to the following relation.

$$\bar{F} = \bar{J} \times \bar{B}$$

The magnetic field intensity distribution necessary to find the forces on the winding of this machine is given in a paper by Kirtley (8), and the following expression for the radial force distribution using the notation shown in figure 2.3 is given by Thullen (5).

J_f = field current density

μ_0 = magnetic permeability of a vacuum

$\eta = \rho/R_1$

ℓ = axial length

R_1 = inner field radius

R_2 = outer field radius

$Y = R_2/R_1$

$$\frac{dF_\rho}{dVol} = -2\frac{J_f^2\mu_0 \; R_1 \; \ell \; \eta}{3\pi} \left(4 - 3\,\frac{Y}{\eta} - \frac{1}{\eta^3}\right) \cos(\delta_p) \; \sin\phi$$

Although the resulting force distribution varies both radially and circumferentially, the integrated radial distribution across the point of maximum forces may be used to estimate the magnetic pressure load. At a current density of 2.5×10^8 amp/m^2, which is the maximum value allowed by the short sample tests of the wire, and the winding geometry, the above expression gives a maximum pressure load of 340 psi for this machine. This pressure must be added to the rotational load to determine the glass prestress needed to prevent separation.

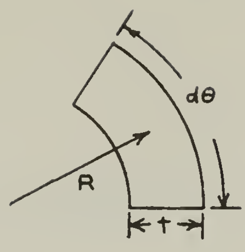
The rotational body force on a thin rotating shell is given by the following expression which is then rearranged to give a pressure.

ω = radian speed of shell

ρ = shell density

P_c = contact pressure

$F = \rho R\omega^2 R d\theta \ell t$



$$\frac{F}{Rd\theta\ell} = P_c = \rho R t \omega^2$$

A force balance on the three layer model assuming no load is carried by the wires and that no pressure exists between the rotor and winding hoop at some rotational speed ω, gives the following expression.

P_{csc} = contact pressure on glass hoop due to rotational body forces on wire hoop

P_{cgl} = equivalent contact pressure on glass hoop due to rotational body forces on glass hoop

P_m = contact pressure on glass hoop due to magnetic body forces on wire hoop

σ_g = glass hoop stress

$$2R_{gi}\ell(P_{csc} + P_{cgl} + P_m) = 2\sigma_g A_g$$

$$A_g = t_g \frac{\ell}{2}$$

Using these equations the stress in the glass at the separation speed ω is given by the following.

ρ_c = density of wire

ρ_g = density of glass

$$\sigma_g = \frac{2}{t_g}\left[\omega^2\left(\rho_c t_c \bar{R}_c R_{gi} + \rho_g \frac{t_g}{2} \bar{R}_g R_{gi}\right) + P_m R_{gi}\right]$$

This stress level is reduced when the machine comes to rest because of the decrease in the rotor size. Using Hooke's Law and relating the strain in the steel rotor to the stress in the glass gives the following expression.

E_g = modulus of elasticity of glass

E_s = modulus of elasticity of steel

ρ_s = density of steel

$$\sigma_g = \frac{\frac{2}{t_g}\left[\omega^2\left(\rho_c t_c \bar{R}_c R_{gi} + \rho_g \frac{t_g}{2} \bar{R}_g R_{gi}\right) + P_m R_{gi}\right] - \omega^2 \frac{E_g}{E_s} \rho_s \bar{R}_s^2}{1 + \frac{E_g\, t_{g/2}}{E_s\, t_s}}$$

The previous expression gives the prestress required to prevent layer separation at a given speed. For layer separation at a speed of 3600 rpm, the prestress required is 9,050 psi. At separation the stress level in the glass is 10,800 psi.

A problem exists in the chosen winding structure because of the differences in thermal contraction between the glass banding and the rotor. As the rotor structure is cooled to operating temperature, the stainless steel shrinks much more

than the banding, thereby reducing the prestress. The thermal contraction of the superconducting wire is very close to that of the rotor and presents no serious problem. The following analysis is used to calculate the required prestress which compensates for thermal contraction differences. This stress may be added to the prestress needed to prevent separation to find the total prestress required.

The change in the prestress level is the result of the difference in the thermal strains of the stainless stell and the glass.

ε_{ts} = thermal strain in steel

ε_{tg} = thermal strain in glass

$$\varepsilon_{ts} - \varepsilon_{tg} = \Delta\varepsilon_t$$

Equating the total strains and using Hooke's law and equilibrium conditions results in an expression for the stress required in the stationary glass hoop assuming the shells just fit at the operating temperature of 4.2°K.

$$\sigma_{g4.2} = \frac{\Delta\varepsilon_t \; (E_{g4.2})}{1 + \frac{A_{g10} \; E_{g4.2}}{A_{s10} \; E_{s4.2}}}$$

For the given geometry and assuming the modulus of elasticity of the stainless steel and glass epoxy banding doesn't change appreciably (9), the prestress required at

room temperature to insure fit at operating temperature is given by the following.

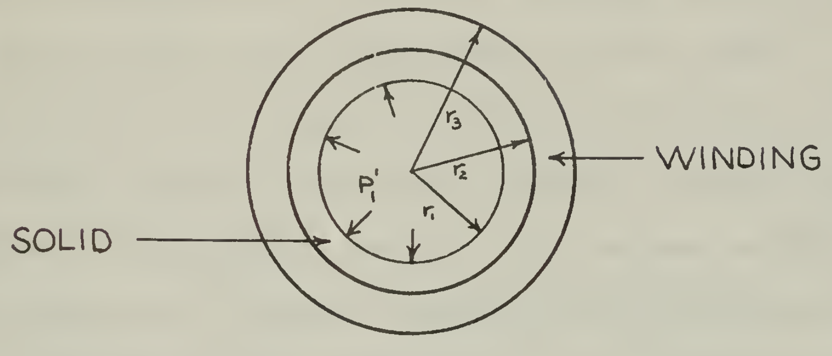
$$\sigma_g = -\sigma_{g4.2}$$

For a difference in thermal strains of -2.54×10^{-3} a 21,800 psi glass prestress is needed. The total prestress required is the sum of this and the prestress needed to prevent layer separation due to magnetic and rotational forces and is 30,850 psi for the constants and dimensions given in Appendix B.

Once the desired prestress level is determined, the required winding tension program may be more realistically determined. The prestress level within the winding layers is a function of the location and winding tension applied when wound. For example, if all layers were wound with the same tension the stress level in the inner fibers would be expected to be less than the outer fibers because of compression by each succeeding layer. The three layer model used determined the uniform prestress level required. This is also the optimum distribution since all fibers are uniformly loaded. However, if the distribution cannot be achieved, a method is needed to find the prestress distribution to satisfy the total stress requirements.

Similar problems are dealt with in construction of thick walled cylinders made to withstand high internal pressures. C. W. Comstock (10) gives the following expression for the

winding tension required to assure uniform prestress in a winding around a hollow cylinder.



σ_ω = winding tension stress

$\sigma_{t''}$ = desired final uniform stress

$$\sigma_\omega = \sigma_{t''} \frac{r_3(r^2+r_1^2) - 2rr_1^2}{r(r^2-r_1^2)} - \frac{2P_1^1 r_1^2}{r^2-r_1^2} \qquad r_2 < r < r_3$$

For our use $P_1^1 = 0$, since there is no internal pressure on the rotor.

D. M. Hewitt (10) gives the tangential stress distribution for the same geometry but wound with constant tension.

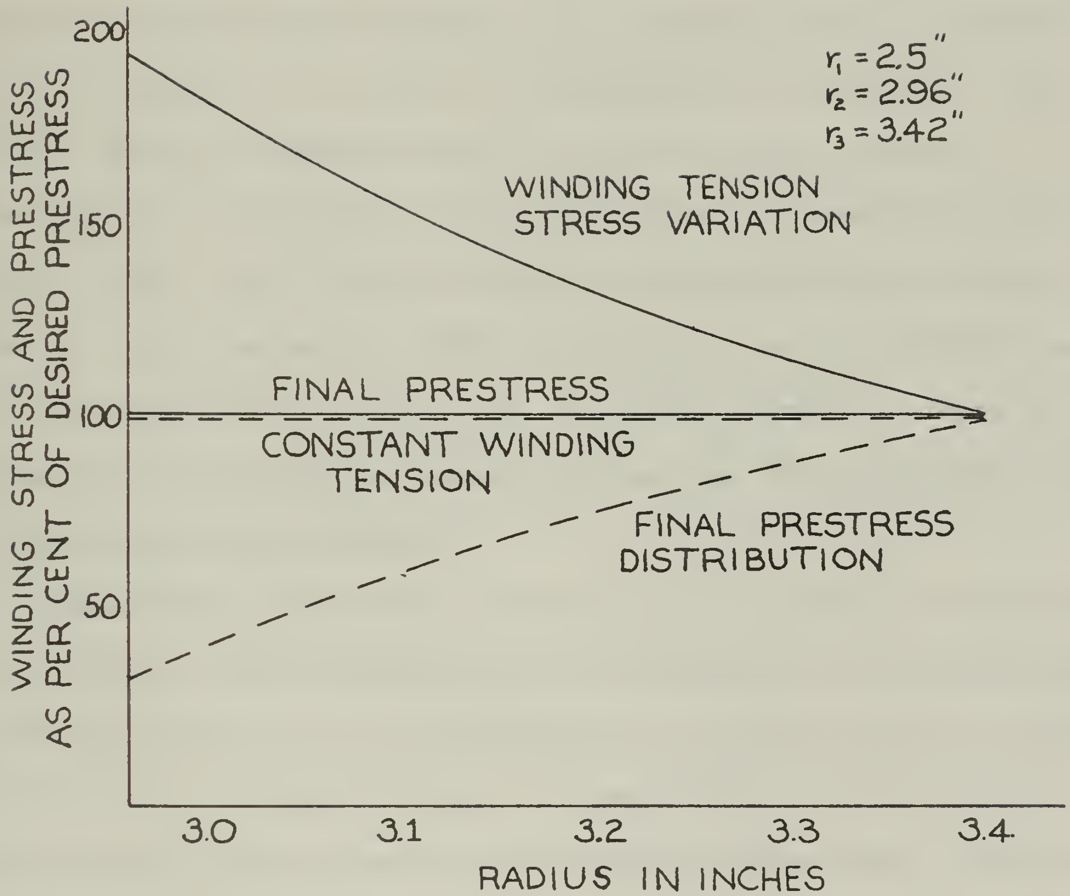
σ_t = final prestress in winding

$$\sigma_t = \sigma\omega(1 - \frac{r^2+r_1^2}{2r^2} \ell n \frac{r_3^2-r_1^2}{r^2-r_1^2})$$

Using these relations, the prestress distribution may be found. Figure 5.2 shows how the distribution varies with winding tension for a geometry consistent with winding the rotor tube with a layer of glass.

The choice of whether to follow one of the two programs depicted or some intermediate tension variation depends principly on whether the stress level needed to follow a program falls within the yield point of the glass. Since the yield point of the glass is about 275,000 psi, even with a large safety factor the optimum winding tension program may be possible. The winding tension jig imposes another constraint, making a constantly varying tension during banding impractical. However, a tension which varies from one banding to the next when constructing the winding provides a reasonable approximation to the optimum.

A recommended banding program is given in table 5.1. Banding stresses are given for each layer of a structure composed of seven 0.065 inch bands which when completed will have an approximately uniform stress level of 50,000 psi.



WINDING TENSION PROGRAMS

FIGURE 5.2

CHAPTER VI

Conclusions and Recommendations

The use of superconductors in electric machinery, whether for large power generation plants, naval propulsion systems, or other applications, will depend upon the satisfactory solution of a number of engineering problems. The solution must be demonstrated by the successful design, construction, and testing of superconducting machines themselves. While this thesis describes one part of the fabrication of an experimental 2MVA alternator, whose success can only be measured by testing the completed machine, certain conclusions may be drawn regarding the use of superconductors for rotating field windings.

Commercially available materials can be used to construct field windings whose superconducting properties are maintained by locating them in a low temperature structure and by cooling the wires with liquid helium. As described in this thesis, high strength epoxy-glass roving materials now used extensively in the aerospace industry can be used in a superconducting field winding support structure.

Rotating field windings for superconducting machines can be constructed without expensive and heavy equipment. Unlike conventional rotors, where the conductors lie in machined slots cut along the rotor, configurations as described in this thesis with a superconducting magnet composed of individually supported layers of coils, offer an alternative to exacting

[illegible]

machining operations used in the manufacture of conventional machines.

While procedures and jigging described in this thesis are for a machine of 2MVA anticipated rating, no restrictions are noted which preclude use of similar jigging and procedures for the construction of the field windings for much larger superconducting machines.

Construction of the field winding for this machine will be a success if prescribed winding procedures and jigging lead to a completed winding which behaves in a predictable manner. It is recommended that a harmonic analysis of the field of the completed machine be compared with design predictions to see whether adequate support has been given superconducting wires.

TABLE 5.1

RECOMMENDED BANDING PROGRAM

The following banding stress levels will approximate a uniform stress level of 50,000 psi in seven 0.065-inch bands.

LAYER	BANDING STRESS IN PSI
1	87,000
2	79,000
3	71,000
4	65,000
5	59,000
6	54,000
7	50,000

APPENDIX A

Material Descriptions

The following data describing the materials used in the construction of the field winding is taken from the manufacturer's product information bulletin for the respective material except where noted.

Superconducting Wire

Manufacturer: Supercon Division of Norton Company, Natick, Massachusetts

Type: T48B

Overall dimensions of matrix: 0.050" by 0.125"

Matrix material: high conductivity copper

Strain material: niobium-48% titanium

Number of strands: 24

Twist of strands: 4 turns/ft.

Area ratio Cu/SC wire: 2.6:1

Matrix coating: copper oxide, 0.0001"-0.0002"

Critical temperature: approximately 10° K

Critical field: 122 kilogauss

Young's modulus at 20° C: 15 x 10^6 psi

Minimum breaking stress at 20° C: 50,000 psi

Glass Roving

Manufacturer: Owens-Corning Fiberglass Corporation
Toledo, Ohio

Type: Fiberglas high tensile strength S-2 continuous roving glass designed for filament winding operations

Number of ends: 20

Virgin tensile strength: 665,000 psi

Yield strength 1000° F: 275,000 psi

Modulus of elasticity at 72° F: 12.4×10^6 psi

Density: 0.090 lbs/in^3

Coefficient of expansion: 3.1 in./in./°F $\times 10^{-6}$

Insulating Tape

Manufacturer: C.P.S. Industries, Inc., Ripco Industrial Division, Franklin, Tennessee

Brand Name: Res-i-glass, Type G

Description: unwoven, semi-cured, fiberglass, thermosetting tape, resin tape

Thickness: 0.015"

Width: 0.25"

Epoxy (9)

Resin formulation by wts: Epon 828/DSA/Empol 1040/BDMA (100/115.9/20/1)

Ingredient	Description and source
Epon 828	Bisphenol-A epoxy; Shell Chemical Co., Plastics and Resins Div., Downey, Calif.

DSA	Dodecenysuccinic Anhydride; Allied Chemical Corporation, New York, N.Y.
Empol 1040	Aliphatic tricarboxy acid (molecular wt. 845); Emery Industries, Inc., Cincinnati, Ohio
BDMA	Benzyldimethylamine; Sumner Chemical Company, New York.

APPENDIX B

The following physical dimensions and constants were used in the stress analysis in Chapter IV.

J_f = 2.5 x 10 amp/m^2

μ_0 = 4πx 10^{-7} volt-sec/amp m.

R_1 = 3.0 inches

R_2 = 4.0 inches

Y = 4.0/3.0

δ_p = 30°

R_{si} = 2.50 inches

$\bar{R}_s$ = 2.73 inches

R_{ci} = 2.96 inches

$\bar{R}_c$ = 3.34 inches

R_{gi} = 3.71 inches

$\bar{R}_g$ = 3.94 inches

ρ_s = 0.282 lbm/in^3.

ρ_c = 0.322 lbm/in^3.

ρ_g = 0.090 lbm/in^3.

t_s = 0.46 inches

t_c = 0.75 inches

t_g = 0.46 inches

ε_{ts} = -0.00304

ε_{tg} = -0.0005

E_g = 10 x 10^6 psi

E_s = 30 x 10^6 psi

[illegible]

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Thesis
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Johnson
Construction of field winding for a superconducting alternator.